Abstract

Homogeneous Charge Compression Ignition (HCCI) combustion is an alternative combustion mode in which the fuel is homogeneously mixed with air and is auto-ignited by compression. Due to charge homogeneity, this mode is characterized by low equivalence ratios and temperatures giving simultaneously low nitric oxide (NO_x) and soot in diesel engines. The conventional problem of NO_x-soot trade-off is avoided in this mode due to absence of diffusion combustion. This mode can be employed at part load conditions while maintaining conventional combustion at high load thus minimizing regulatory cycle emissions and reducing cost of after-treatment systems. The present study focuses on achieving this mode in a turbocharged, common rail, direct injection, four-cylinder, heavy duty diesel engine. Specifically, the work involves a combination of three-dimensional CFD simulations and experiments on this engine to assess both traditional and novel strategies related to fuel injection.

The first phase of the work involved a quasi-dimensional simulation of the engine to assess potential of achieving HCCI. This was done using a zero-dimensional, single-zone HCCI combustion model with n-heptane skeletal chemistry along with a one-dimensional model of intake and exhaust systems. The feasibility of operation with realistic knock values with high EGR rate of 60% was observed. The second aspect of the work involved three-dimensional CFD simulations of the in-cylinder process with wall film prediction to evaluate injection strategies associated with Early Direct Injection (EDI). The extended Coherent Flame Model-3Zone (ECFM-3Z) was employed for combustion simulation of conventional CI and EDI, and was validated with experimental in-cylinder pressure data from the engine. A new Uniformity Index (UI) parameter was defined to assess charge homogeneity. Results showed significant in-homogeneity and presence of wall film for EDI. Simulations were conducted to assess improvement of charge homogeneity by several strategies; narrow spray cone angle, injection timing, multiple injections, intake air heating, Port Fuel Injection (PFI) as well as combination of PFI and EDI. The maximum UI achieved by EDI was 0.78. The PFI strategy could achieve UI of 0.95; however, up to 50% of fuel remained trapped in the port after valve closure. This indicated that except EDI, none of the above-mentioned strategies could help achieve the benefits of the HCCI mode.

The third part of the work involved engine experimentation to assess the EDI strategy. This strategy produced lower soot than that of conventional CI combustion with very short combustion duration, but led to high knock and NO_x which is attributed to pool fire burning phenomenon of the wall film, as confirmed by CFD. An Optimized EDI (OptimEDI) strategy was then developed based on results of CFD and Design of Experiments. The OptimEDI consisted of triple injections with split ratio of 41%-45%-14% and advancing the first injection. This strategy gave 20% NO_x and soot reduction over the conventional CI mode. Although this strategy gave encouraging results, there was a need for more substantial reduction in emissions without sacrificing efficiency. Hence, a novel concept of utilizing air-assisted Injection (AAI) into the EGR stream was employed, as this implied injecting very small droplets of fuel into the intake which would have sufficient residence time to evaporate before reaching the cylinder, thereby enabling HCCI. The fourth and final part of the work involved engine experimentation with AAI, and combination of OptimEDI with AAI. Results with 20% EGR showed that 5 to 10% of AAI gave further reduction in NO_x but not in soot. With experiments involving 48% EGR rate, there was soot reduction of 75% due to combined AAI-EDI. NO_x was negligible due to the high EGR rate. Thus, the significant contribution of this work is in proving that combining AAI with EDI as a novel injection strategy leads to substantial NO_x and soot reduction.